Selective Conversion of Glucose to Fructose with Immobilized Tertiary Amines

Undergraduate Research Thesis

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Abstract

Increasing global energy demands necessitate research in alternative sources of energy such as biomass. Sustainable biomass conversion strategies require high yields for the isomerization reaction of glucose to fructose. The key challenge for this reaction is achieving high selectivity towards fructose using inexpensive catalytic materials. Previous studies have achieved 32% fructose yields using tin-containing catalysts (Sn-BEA zeolite) and homogeneous organic bases (triethylamine), but these catalysts are either expensive to synthesize or require energy-intensive downstream separation processes. By functionalizing a mesoporous silica material with a triethylamine analogue, we combined aspects of these studies to create an improved heterogeneous catalyst to convert glucose to fructose. Preliminary results highlighted important acid-base interactions between the catalyst surface and active site; namely, the acidic surface silanols were quenching the nitrogen base, hindering its ability to perform catalysis. By increasing the density of catalytic groups on the surface and shortening the linker length between the catalyst surface and the active site nitrogen, the fructose yield was increased to 20%. However, catalyst activity decreased with successive catalyst use, and elemental analysis confirmed catalyst leaching as a barrier to catalyst reusability. Future studies should focus on reducing organosilane leaching to further improve the catalyst for industrial applications. Overall, this study developed an effective catalyst for improving biomass upgradation processes, overcoming previous hurdles that involved expensive syntheses and separations.

Acknowledgements

First, I would like to thank Dr. Brunelli for all of his support and guidance throughout this project. I would additionally like to thank all of the graduate and undergraduate students in the Brunelli Lab, specifically Mariah Whitaker and Nitish Deshpande. Mariah, thank you for training me on synthesis and characterization techniques. Nitish, thank you for helping me synthesize and characterize catalysts, run reactions, build plots for this report, and forcing me to think about my project on a deeper level. Without your help, this work would not have been possible.

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Introduction

Increasing global energy demand requires innovative and sustainable methods to produce chemicals and fuels such as conversion of biomass. A highly desirable biomass conversion strategy generates 5-hydroxymethylfurfural (HMF) as an intermediate. HMF has been recognized as the top priority chemical to produce from biomass because it can be used to create petroleum-derived commodity chemicals such as p-xylene, plastics, and fuels, helping reduce oil dependency worldwide.[1] Figure 1, below, shows several high-value chemicals that can be synthesized from HMF. Highlighted in the figure is 2,5-furandicarobxylic acid (FDCA) which has the potential to replace terephthalic acid (PTA) in the synthesis of plastics.[2]

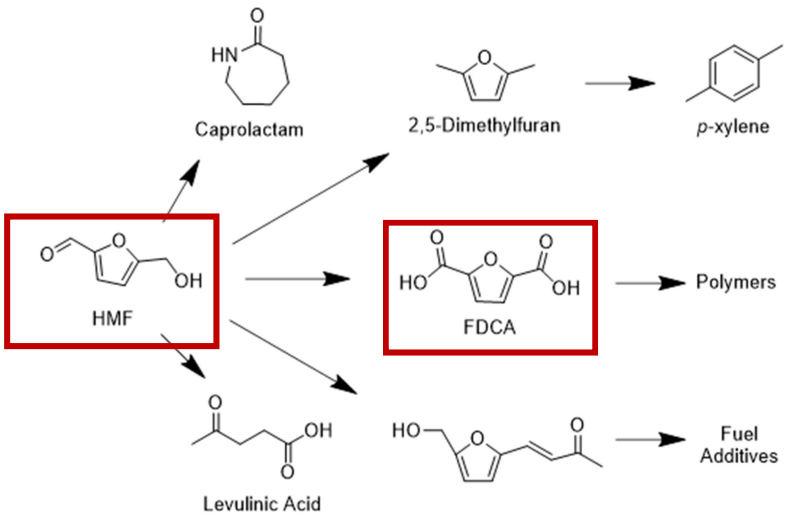

Figure 1: Depiction of chemicals that can be synthesized from HMF and their applications

HMF is commonly produced from the dehydration of fructose. Since fructose itself is a relatively expensive starting material, a cheaper strategy would involve first isomerizing glucose to fructose, then performing the dehydration to generate HMF. This study will attempt to improve the glucose to fructose isomerization selectivity.

Commercially, the isomerization reaction uses enzymes, but this process is unfavorable as it requires extensive pre-reaction purification and highly specific temperature and pH control.[3]

Previous studies have attempted to increase the selectivity and yield of this reaction by using both homogenous and heterogeneous methods. More recently, researchers have shown that the isomerization reaction can be catalyzed via Lewis acid sites in Sn-BEA zeolite.[4] While the use of Sn-BEA allows for the efficient removal of the catalyst from the product through simple filtration, it is undesirable because of the difficulty in synthesizing Sn-BEA on a large scale.[4] Researchers have also been successful in catalyzing the reaction with triethylamine, an organic base.[5] Although inexpensive and readily available, triethylamine is undesirable because of the energy-intensive difficulties involved in its separation from the reaction media. So, a truly sustainable method to convert glucose to fructose remains to be found.

The goal of this project was to develop a unique catalyst to sustainably and selectively convert glucose to fructose. The catalyst support of choice was SBA-15, a mesoporous silica framework. SBA-15 was not only capable of offering shape-selectivity to the reaction, but it also allowed for functionalization of multiple species onto its surface, providing an enzyme-like active site.[6] Since SBA-15 is a solid support, it was separated from the reaction mixture through mechanical filtration, just as with Sn-BEA. However, synthesis of mesoporous SBA-15 is both simpler and cheaper than that of Sn-BEA because of the expensive structure directing agents, exhaustive crystallization periods, and costly safety measure induced by HF use in the latter's synthesis.[4]

The original hypothesis consisted of synthesizing a catalyst by immobilizing (N,N-Diethyl-3-aminopropyl)trimethoxysilane (the triethylamine analogue) onto the surface of mesoporous SBA-15. A molecular representation of this catalyst can be found in Figure 2.

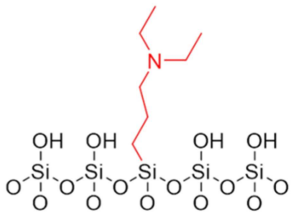

Figure 2: Molecular representation of catalyst structure with TEA analogue functionalized to SBA-15 support

Next, the microenvironment of the active site was tuned to optimize catalytic performance. Namely, an unfavorable nitrogen-silanol interaction was identified and was strategically altered so as to increase reaction conversion. First, these silanols were capped using hexamethyldisilazane (HDMS), a common reagent used to remove silanols from mesoporous silica materials. However, this method did not prove effective. Alternative hypotheses included increasing the density of catalytic species on the surface (thereby consuming available silanol space) and reducing the propyl linker connecting the silicon and nitrogen atoms to a methyl linker. Only by using these methods was reaction conversion successfully increased without compromising selectivity towards fructose.

Materials and Methods

The catalyst support of choice was SBA-15, a mesoporous silica molecular sieve with hexagonal pores ranging from 5 to 15 nm in diameter. Synthesis was based on a verified procedure from literature[6] where a triblock copolymer, P-123, was suspended in water at a critical concentration. At this concentration the polymer spontaneously forms micellular rods in solution. Tetraethylorthosilicate was then added dropwise to the solution, allowing the silica to condense around the structure formed by P-123. The resultant structure was then calcined to burn off the polymer templating agent to leave a porous silicon-oxygen framework. Figure 3 illustrates this synthesis procedure.

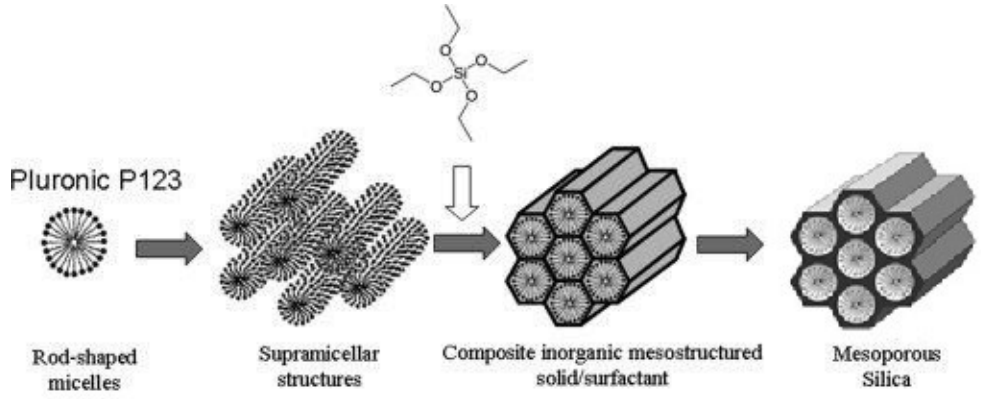

Figure 3: SBA-15 synthesis procedure[7]

Each catalyst was grafted onto the SBA-15 using a robust method involving an organosilane. An organosilane is composed of an organic head group attached to a silicon atom that is further bonded to three alkoxy species. The alkoxy species are hydrolytically unstable and bind with hydroxyl groups on the surface of SBA-15 to produce an organic-functionalized surface. Suspensions of bare SBA-15 and toluene were allowed to mix at room temperature for several hours, small quantities of organosilane were added to this mixture and stirred for 24

hours, and the final mixture was heated to 80°C and further stirred for 24 hours. Before the temperature was raised, a small quantity of water was added to this mixture, initiating the functionalization. After the third mixing period, the suspension was filtered, isolating the catalyst. The diagram below shows this procedure on the atomic level using (N,N-Diethyl-3-aminopropyl)trimethoxysilane as the organosilane.

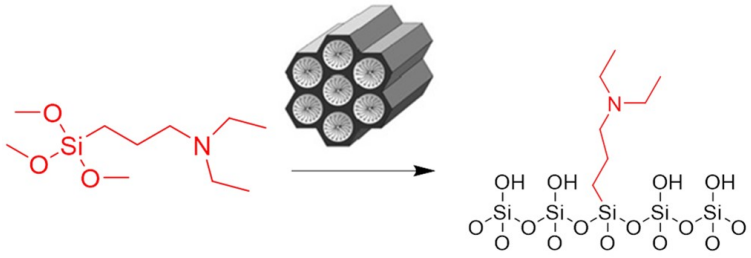

Figure 4: Organosilane functionalization procedure for TEA analogue

The surface capping of SBA-15 hydroxyls followed a similar procedure to the organosilane functionalization. An excess of HMDS reagent was added to functionalized SBA-15 suspended in toluene, allowed to mix at room temperature for 24 hours, and heated to 80°C for another 24 hours. Next, the mixture was filtered to obtain the HDMA-capped catalyst.

To assess whether or not the catalysts had been correctly synthesized, three primary characterization techniques were used. Nitrogen physisorption was used to determine the pore size and volume of the catalyst. In this technique, the catalyst sample was cooled to the temperature of liquid nitrogen and was subsequently dosed with nitrogen gas. The pressure was altered during this dosage period and the adsorption and desorption into the material were recorded. Resulting analysis determined the pore size distribution and pore volume, and these data were compared to standards available in literature to ensure an appropriate match.

Thermogravimetric analysis was used to quantify the loading of organic groups on the surface of the catalyst support. Small quantities of functionalized SBA-15 were placed in a crucible and slowly heated to a temperature of 900 °C in the presence of oxygen. During this heating period, organic species were burned from surface, and the resulting change in mass was detected by the instrument. Based on this mass change, a numerical value for the organic catalyst loading was determined. Elemental analysis was similarly used to quantify loading of organic groups via combustion analysis, but this technique was outsourced for better accuracy.

Selectivity and conversion for each catalyst were determined through reaction testing. 2 grams of a 10 wt% glucose solution were loaded into a 15 mL pressure tube containing a magnetic stir bar. 10 mole percent catalyst was added to each reaction with respect to the moles of glucose present in solution (moles catalytic nitrogen/moles glucose = 0.1). The pressure tube was then inserted into an oil bath set to 100°C, and the reaction was allowed to proceed for a specified time period. The post reaction contents were quenched in an ice bath for 20-30 mins and diluted with a solution of 0.3 M mannitol. This mixture was filtered through a nylon syringe filter and analyzed with High Performance Liquid Chromatography (HPLC). The HPLC peak areas corresponding to glucose and fructose were compared to calibration standards for the column and used to calculate the glucose conversion and fructose selectivity of each reaction.

Results

The first catalyst was synthesized with (N,N-Diethyl-3-aminopropyl)trimethoxysilane at a theoretical density of 0.5 mmol organosilane per gram dry silica. Elemental analysis reported a value of 0.52 mmol/g for the density, so the catalyst will be designated C3-0.52 based on the linker length and the experimental density. This catalyst was next tested for activity in regards to the glucose to fructose isomerization, and the results of this catalyst compared to triethylamine are shown below.

Table 1: Catalytic testing results for initial SBA-15 material with TEA analogue compared to triethylamine

Catalyst	Time (h)	% Glucose Conversion	% Fructose Selectivity
C3-0.52	24	9	57
Triethylamine [1]	0.5	57	54

While the catalyst does show activity for the isomerization reaction, it falls short of the values achieved by triethylamine. A possible reason for the decreased conversion with the SBA-15 catalyst is an acid-base interaction between the surface silanols and the catalytic nitrogen group. Such an interaction would quench the catalyst and render it ineffective; a depiction of this interaction is shown below.

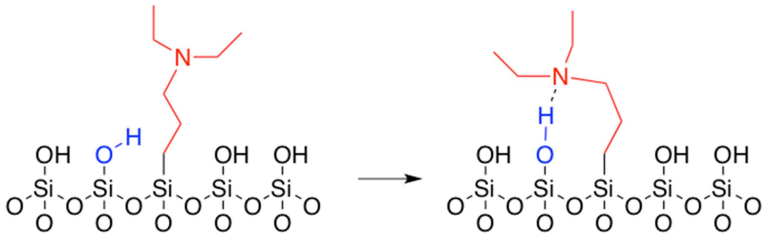

Figure 5: Potential OH-N quenching interaction responsible for low conversion

Three hypotheses were generated to eliminate this unfavorable interaction:

(1) Remove the silanols completely by capping them with hexamethyldisilazane (HMDS).

(2) Strategically reduce the density of silanols groups by increasing the number of catalytic nitrogen groups on the surface.

(3) Reduce the length of the carbon linker length attaching the nitrogen atom to the silicon atom from a flexible propyl group to a rigid methyl group.

To test the first hypothesis, a batch of SBA-15 was synthesized and functionalized with (N,N-Diethyl-3-aminopropyl)trimethoxysilane. Half of this batch was filtered and saved for reaction while the other half was capped with HMDS. The capping of the silanols should eliminate the proposed hydrogen bonding interaction, as shown below.

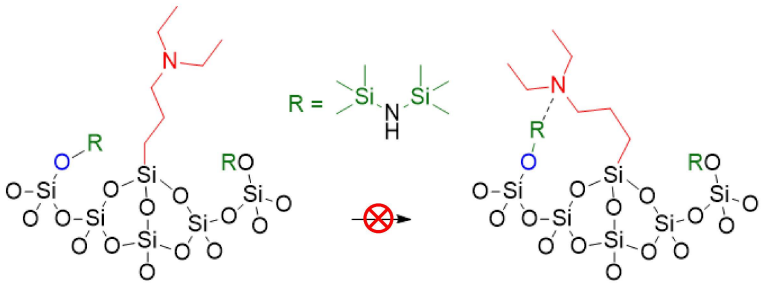

Figure 6: Depiction of HMDS-capped material and subsequent reduction of silanol interactions

Elemental analysis reported an amine density of 0.44 mmol/g for both catalysts, so they are designated C3-0.44 and C3-0.44-HMDS. The nitrogen physisorption and TGA plots for both of these materials can be found in Figures A1 and A2 in Appendix A: Characterization Data. Next, this catalyst was tested for activity in the isomerization reaction, and this data is shown in Table 2.

Table 2: Comparison of HMDS-capped catalyst to original TEA analogue design

Catalyst	Time (h)	% Glucose Conversion
C3-0.44	24	7
C3-0.44-HMDS	24	3

Capping the silanols transitions a hydrophilic environment into a hydrophobic environment, but as clearly shown from the catalytic testing data, makes no improvement to glucose conversion after 24 hours. So, perhaps a hydrophilic environment is necessary for the reaction to proceed. The next hypothesis keeps this property of the local environment intact while simultaneously reducing the density of surface silanols by increasing the loading of nitrogen groups, resulting in the following:

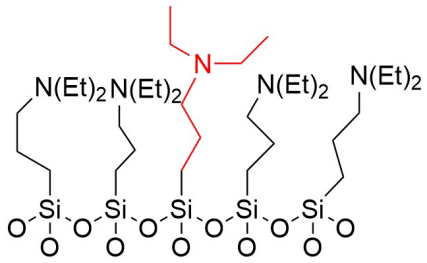

Figure 7: Molecular depiction of high density catalyst materials

Two higher density materials were synthesized and analyzed with TGA and nitrogen physisorption, and the characterization data for all C3 materials (including C3-0.52) can be found in Figures A3 and A4 in Appendix A. These catalysts were also examined with elemental analysis, and the data for the three catalysts are shown below.

Table 3: Elemental analysis results for C3 materials

Catalyst Desgination	Theoretical Loading (mmol/g)	Elemental Analysis Loading (mmol/g)
C3-1.46	2.00	1.46
C3-0.85	1.00	0.85
C3-0.52	0.50	0.52

At higher loadings, the surface of the SBA-15 becomes saturated in that few hydroxyl groups remain for organosilane binding. This explains the lower experimental densities compared to theoretical densities for the C3-0.85 and C3-1.46 catalysts. Figure 8, below, shows the reaction data for each of these three catalysts.

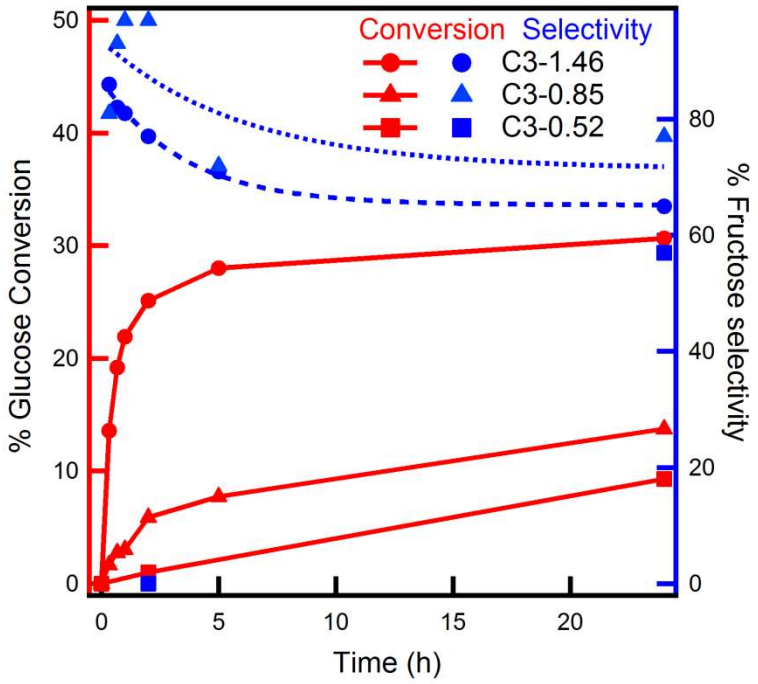

Figure 8: Catalytic testing results for C3 materials comparing effects of amine density

Increasing the surface density has a positive effect on catalyst activity, even when the reaction conditions are normalized. Thus, local surface effects of the catalyst structure must influence the reaction to some extent. However, even the best catalyst, the C3-1.46 material, reaches a maximum yield of 18%, short of the 32% achieved by TEA homogeneously.

In an attempt to increase the fructose yield further, hypothesis three was enacted by synthesizing a material using (N,N-Diethyl-3-aminomethyl)trimethoxysilane, an organosilane that has a single carbon methyl linker rather than the propyl linker used in previous experiments. Catalytic testing in comparison to a similar to the C3-0.52 propyl material yielded the following graph.

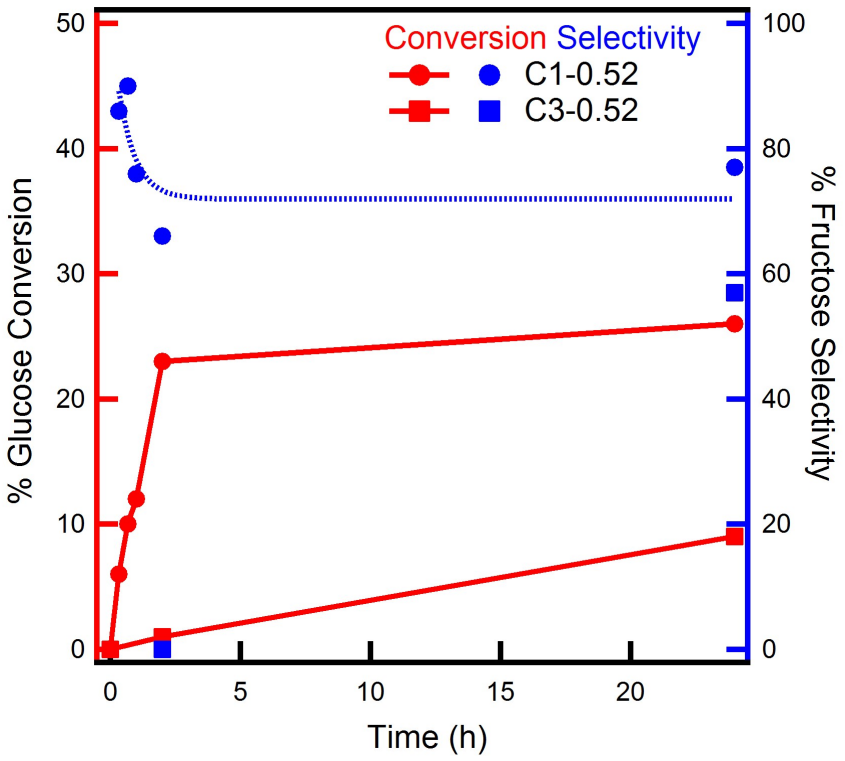

Figure 9: Direct comparison of C1 and C3 materials at 0.52 mmol/g to determine effect of linker length

As the linker length is decreased from a three-carbon linker to a one-carbon linker, the conversion and selectivity rise dramatically over the course of 24 hours. Therefore, the hypothesis connecting linker length to rigidity and subsequently to hydrogen bonding interactions was supported.

Seeing that hypotheses two and three successfully increased the fructose yield, it was decided to combine these two ideas and synthesize a methyl-linked catalyst at a high surface loading. According to elemental analysis, the density achieved led to a catalyst designated C1-0.95. Again, nitrogen physisorption and TGA for both the C1-0.52 and C1-0.95 catalysts can be found in Figures A5 and A6 in Appendix A. Comparison of C1-0.95 with the most successful catalyst to date, the C3-1.46 catalyst, yielded the following.

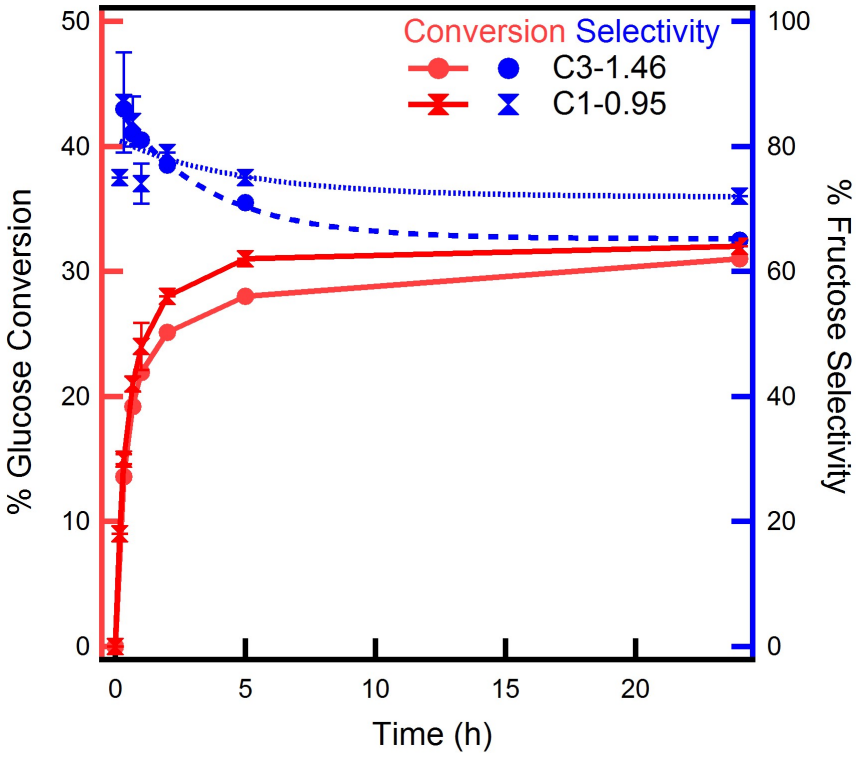

Figure 10: Comparison of best catalysts synthesized: C3-1.46 and C1-0.95

Decreasing the number of carbon linkers between the silicon atom and the catalytic nitrogen further improved the conversion, resulting in a final yield of approximately 20%. While this fell slightly short of the 32% achieved by Sn-BEA and triethylamine, the designed catalyst boasted several improvements over these two methods, including economically/energy-friendly synthesis and separation procedures.

While the performance of the catalyst in a single-use setting was exciting, to properly assess its effectiveness, the catalyst's reusability was tested. The two best catalysts, C1-0.95 and C3-1.46, were used in reaction, filtered, washed with water, and reused in reaction. The following results were obtained after five hours:

Table 4: Catalytic testing results from reuse experiments of C3-1.46 and C1-0.95 before and after a single use

Catalyst	Fresh	Use 1
	% Conversion (%Selectivity)	% Conversion (%Selectivity)
C3-1.46	28 (71)	3 (62)
C1-0.95	31 (75)	18 (76)

Even after a single use, a significant decrease in conversion was observed for both C1 and C3 high density materials. Elemental analysis of each catalyst post-reaction highlighted an important problem; namely, that the TEA-like catalyst was leaching from the SBA-15 support. Upon repeating the reuse process and analyzing the catalyst post-use with elemental analysis, the following data were obtained.

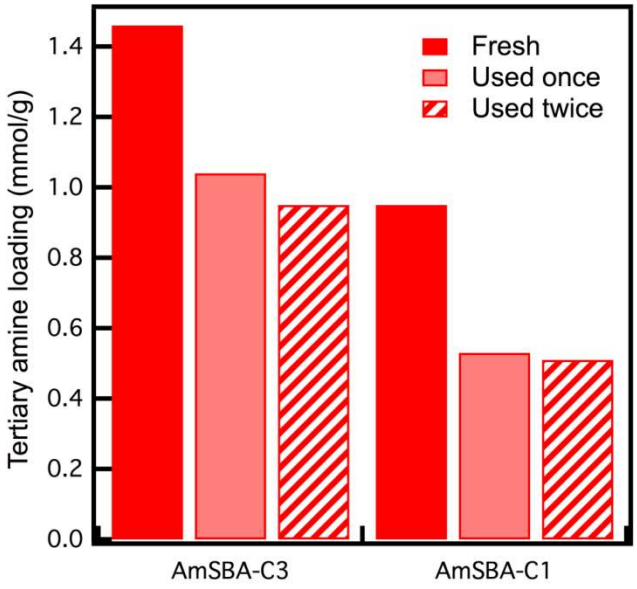

Figure 11: Elemental analysis results of catalysts comparing density of C3-1.46 and C1-0.95 after 0, 1, and 2 uses

After the first use, the density of catalytic species on the surface decreased. However, this decrease levels out after the second use, suggesting only an initial leaching event. Regardless, the decrease in catalytic activity is concerning, and future work will focus on preventing this phenomena by investigating other support species that are more hydrolytically stable (i.e. deviating from Si-O linkages).

Conclusions and Future Work

Efficient biomass upgradation requires novel catalytic methods to selectively produce the desired chemicals and fuels. A popular route for biomass conversion to fuels involves the isomerization of glucose to fructose. Industrially, this reaction employs glucose isomerase, an enzyme susceptible to temperature and pH-based damage. Attempts to replace glucose isomerase have proven expensive to synthesize or involve costly downstream separation processes, so this research focused on producing a sustainable alternative to glucose isomerase.

A TEA-like molecular analogue was functionalized onto the surface of SBA-15 and showed catalytic activity, but the reaction conversion was much less than that seen with homogeneous TEA. Further investigation identified a nitrogen-silanol hydrogen bonding interaction that seemed to deactivate the catalyst earlier than expected. Several hypotheses were generated to address this problem.

First, the silanols were capped with HMDS, a common procedure observed in literature. However, this transformed the microenvironment from hydrophilic to hydrophobic and led to a decrease in conversion over a similar timescale, suggesting that a hydrophilic environment was favorable. The next hypothesis involved using a higher density of catalytic species on the surface to systematically reduce the number of silanols and thus the nitrogen-silanol interactions. At higher densities, the reaction conversion increased dramatically, supporting the theory behind this idea. The last hypothesis entailed shortening the flexible propyl linker connecting the silicon and nitrogen atoms to a rigid methyl linker to statistically reduce the likelihood of the hydrogen bond from occurring. Again, making this change significantly increased the reaction conversion. Combining the two latter hypotheses produced a catalyst capable of selectively generating fructose with a 20% yield.

Catalyst reuse testing showed significant loss in conversion after the first run. Elemental analysis confirmed organosilane leaching as a potential cause of this problem; the density of catalytic species on the surface decreased by approximately 0.4 mmol/g after a single use. Thus, future work should focus on fixing this problem. A possible strategy is to investigate different catalyst frameworks that do not rely on hydrolytically unstable bonds.

Broadly, this works has shown the importance of specific molecular interactions on the effectiveness of a chemical reaction. This type of detailed analysis will be necessary to produce the next generation of catalytic materials. In the 21st Century, selectivity is key, and only by finely tuning the microenvironment of these catalysts can we hope to meet the energy demands of a growing population.

Appendix A: Characterization Data

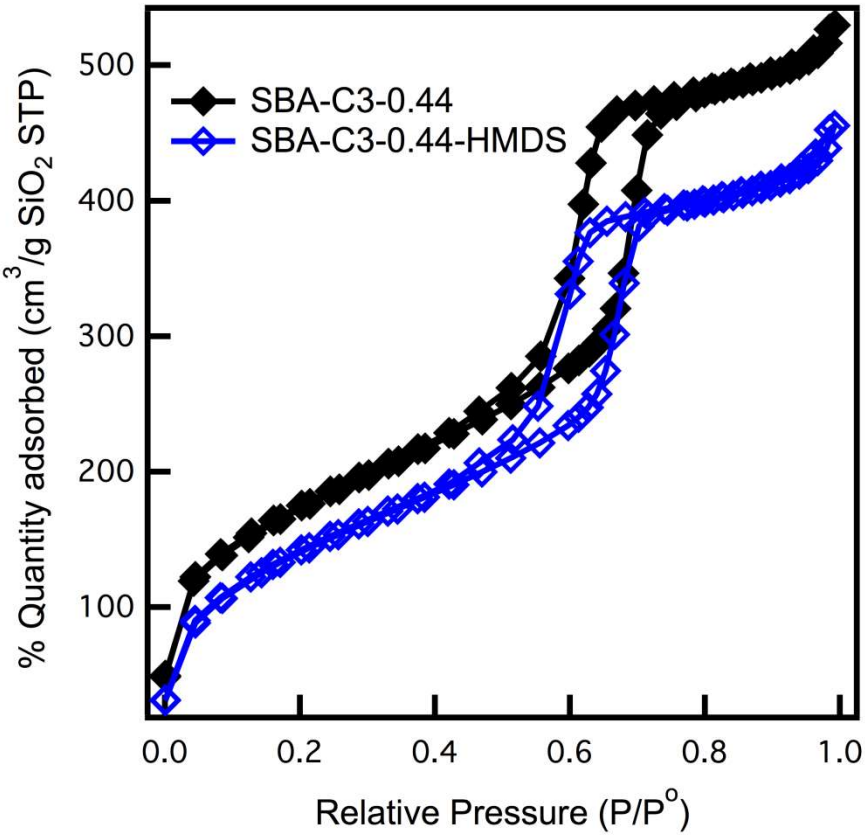

Figure A1: Nitrogen physisorption results comparing C3-0.44 material to C3-0.44 capped with HMDS. The capped material has lower adsorption capacity, indicating successful functionalization of HMDS.

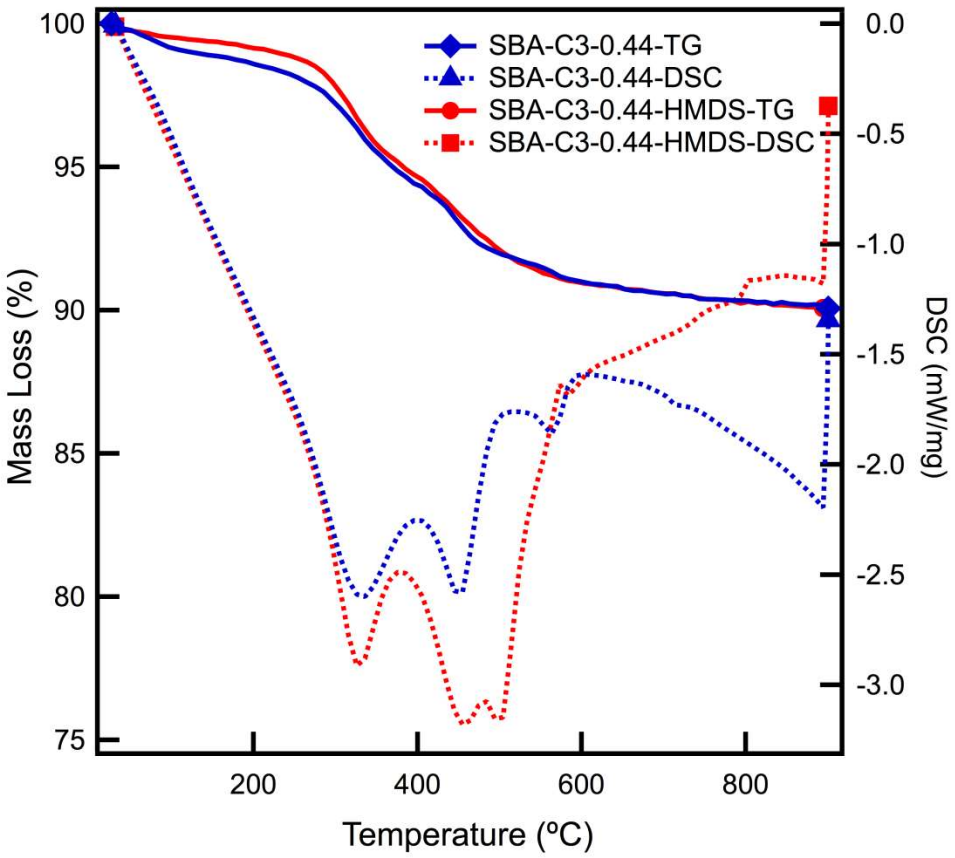

Figure A2: TGA and DSC results for C3-0.44 and C3-0.44-HMDS show that the latter has an additional DSC peak at ~500°C, confirming the presence of HMDS.

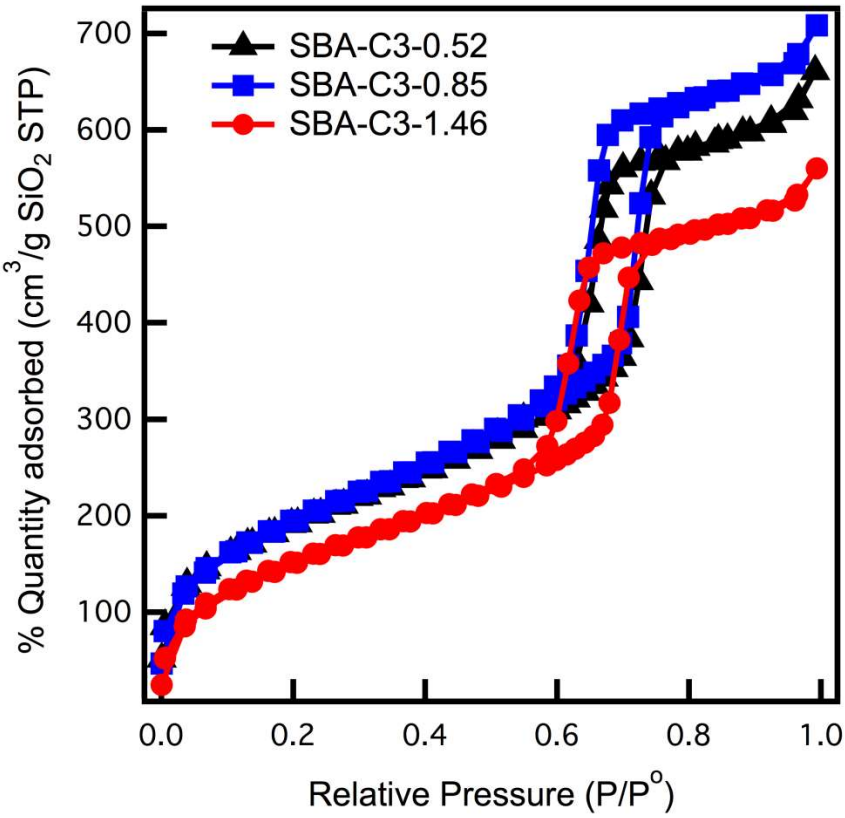

Figure A3: Nitrogen physisorption data for C3-0.52, C3-0.85, and C3-1.46 showing decreased adsorption capacity for higher density materials, supporting proper functionalization of organosilanes

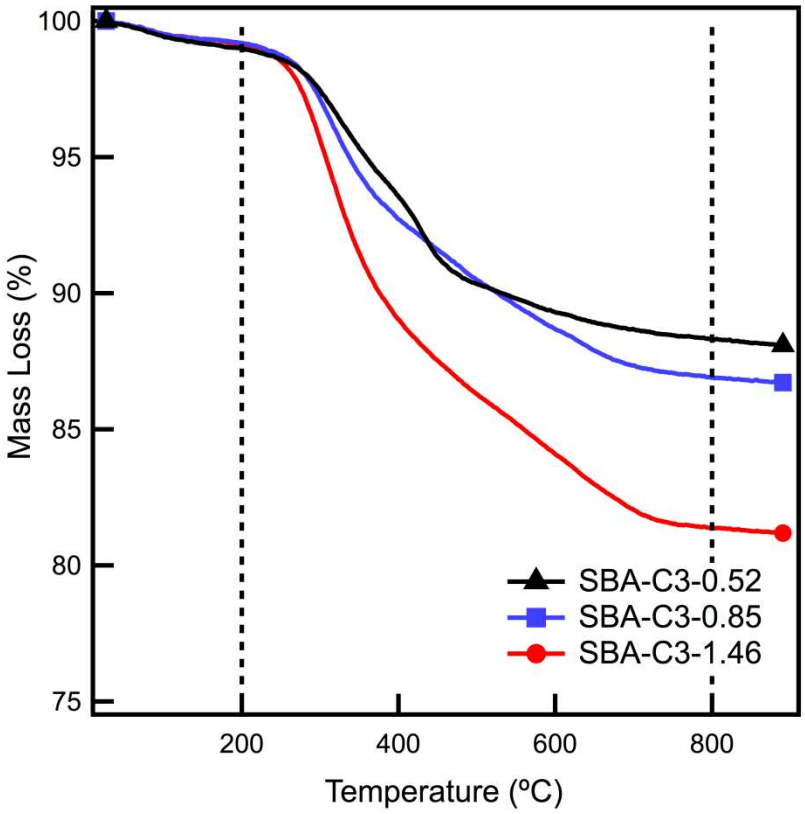

Figure A4: TGA data for C3-0.52, C3-0.85, and C3-1.46 show increased percent mass loss for higher density materials, supporting proper functionalization.

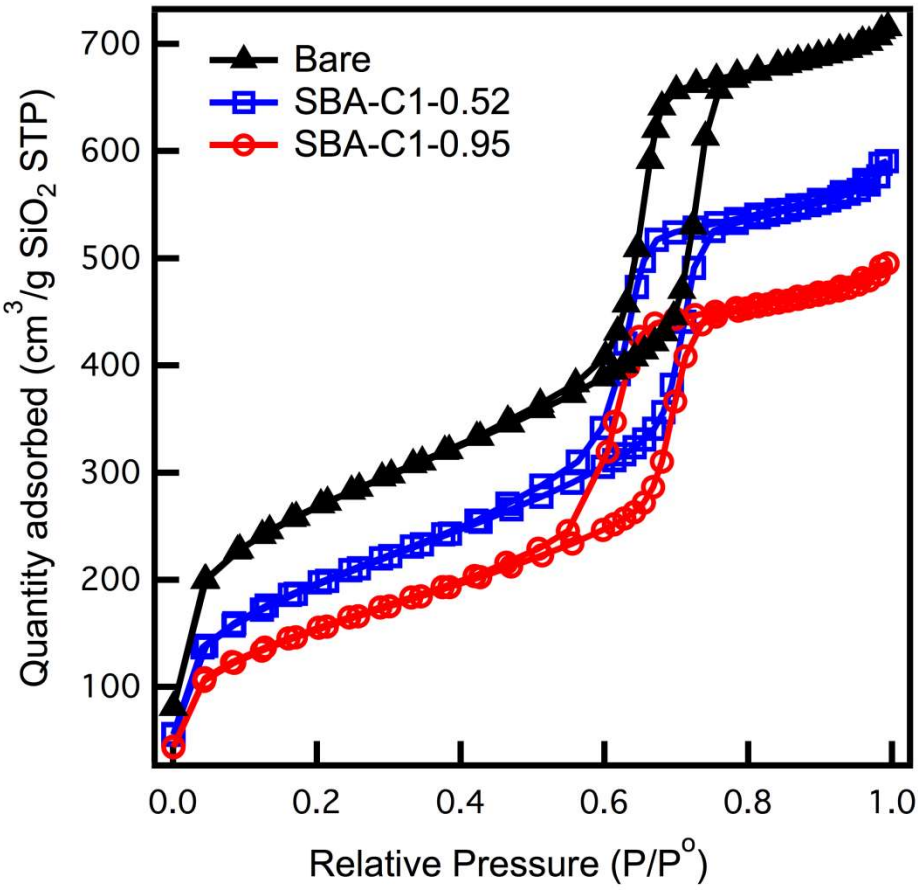

Figure A5: Nitrogen physisorption data for base SBA-15, C1-0.52, and C1-0.95 showing decreased adsorption capacity for higher density materials, supporting proper functionalization of organosilanes.

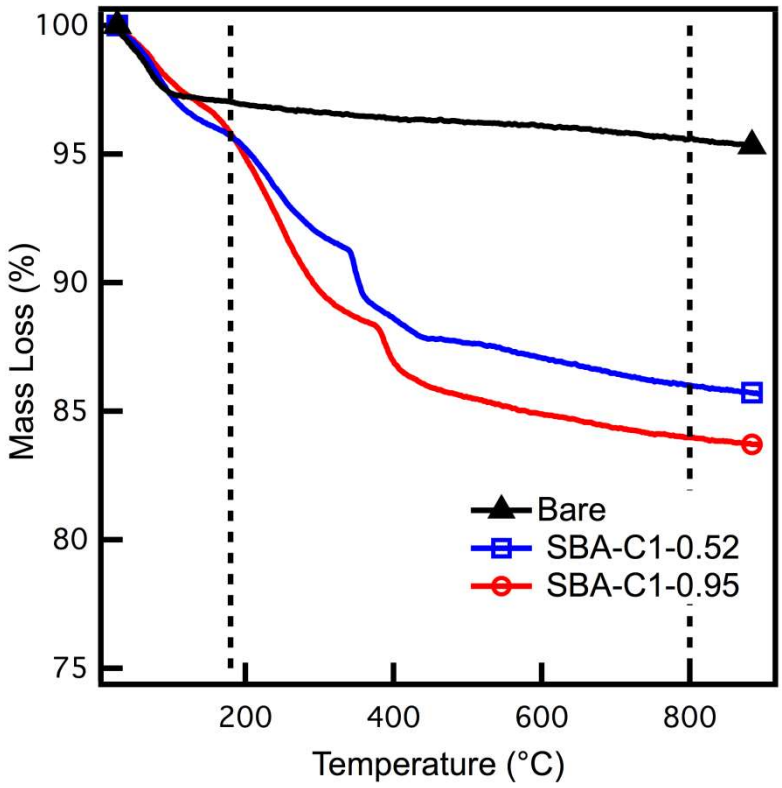

Figure A6: TGA data for C1-0.52 and C1-0.95show increased percent mass loss for higher density materials, supporting proper functionalization.

Appendix B: Works Cited

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